

5                   MULTIPLE BANDWIDTH AMPLIFIER CONTROL SYSTEMS  
                    FOR MOBILE STATIONS AND METHODS THEREFOR

                    FIELD OF THE INVENTIONS

10                   The present inventions relate generally to control systems, and more  
                    particularly to control circuits for transmitters in mobile communication devices,  
                    combinations thereof and methods therefor.

15                   BACKGROUND OF THE INVENTIONS

20                   Power control systems are known generally. In analog control  
                    circuits, an amplifier output power is detected by a peak-detect circuit, which is  
                    coupled to an integrator. An output of the integrator controls the amplifier in a  
                    manner that tends to match the output of the peak-detect circuit with a reference  
                    signal to the integrator.

25                   U.S. Patent No. 4,458,209 entitled "Adaptive Power Control Circuit",  
                    assigned commonly with the present application, discloses a dual band analog  
                    control loop having an integrator with a variable response time provided by  
                    switching first and second resistors of an RC time constant. The faster time  
                    constant applies to transient operation and the slower time constant to steady-state  
                    operation. See also, U.S. Patent No. 5,697,074 entitled "Dual Rate Power Control  
                    Loop For a Transmitter".

30                   In digital control circuits, the peak detect circuit output is filtered  
                    and converted to a digital format before being input to a processor, which  
                    provides an output control signal based on a comparison of the digitized input  
                    signal with a reference signal. Like the analog control circuits discussed above,

digital control circuits control the amplifier in a manner that tends to match the digitized peak-detect circuit signal with the reference signal. Digital processing however runs generally at a slower rate than the modulation rate of the peak-detect circuit signal so that variation of the envelope is tracked poorly or not tracked at all. Another limitation of known digital control circuits is that a D/A converter at the output of the processor is written initially with an estimated value, which requires knowledge of gain at the start of the transmit sequence for acceptable performance. The estimated value moreover is susceptible to variations in temperature, voltage, load and other conditions. U.S. Patent No. 5,287,555 entitled "Power Control Circuitry for A TDMA Radio Frequency Transmitter", the subject matter of which is incorporated by reference herein.

The various aspects, features and advantages of the present invention will become more fully apparent to those having ordinary skill in the art upon careful consideration of the following Detailed Description of the Invention with the accompanying drawings described below.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an analog implementation of a control circuit according to a first exemplary embodiment of the invention.

FIG. 2 is a look up table for storing estimation mode operation reference signals for different output power levels.

FIG. 3 is an exemplary TDMA transmitter having a digital control circuit.

FIG. 4 is a timing signal diagram illustrating TDMA burst operation according to an exemplary embodiment of the invention.

FIG. 5 is an exemplary EDGE transmitter having a digital control circuit.

5                    FIG. 6 is a timing signal diagram illustrating EDGE burst operation according to an exemplary embodiment of the invention.

FIG. 7 is an exemplary GSM transmitter having a digital control circuit.

10                   FIG. 8 is a timing signal diagram illustrating GSM burst operation according to an exemplary embodiment of the invention.

## DETAILED DESCRIPTION OF THE INVENTIONS

15                   The present invention relates to control systems and circuits and methods therefore, which are suitable for implementation in mobile communication device transmitters, for example, in cellular telephone handsets, pagers, wireless enabled personal digital assistants and other wireless communication devices.

20                   FIG. 1 is an exemplary RF amplifier and control circuit 100 comprising generally an amplifier 110 and a vector modulator 120 having an output coupled to an input of the amplifier by an RF modulator 130, which converts vector modulation from the modulator to the RF operating frequency of the amplifier. The amplifier 110 includes generally a control input and may  
25                   comprise a chain or several stages as is known in the art.

5      The control circuit also comprises generally a proportional control circuit and an integral control circuit. In one embodiment, the proportional control circuit includes an input coupled to a first reference signal source and an output coupled to the control input of the amplifier. The integral control circuit integrates an output of the amplifier relative to a reference signal and includes an integrator control signal output coupled to the control input of the amplifier.

10      In the exemplary embodiment of FIG. 1, an op-amp 140 having an output coupled to the control input of the amplifier 110 is configurable as a unity gain buffer circuit and as an integrator circuit, which constitute the proportional and integral control circuits, respectively.

15      In FIG. 1, the output of the amplifier is coupled generally to an input of the op-amp 140, for example by a non-linear device. In FIG. 1, a peak-detect circuit 150 interconnects the amplifier output to the op-amp input.

20      In an initial mode of operation, referred to herein as the "Estimation Mode", the proportional control circuit applies an initial control signal to the control input of the amplifier by applying a first reference signal to the proportional gain control circuit.

25      During estimation mode, the reference signal applied to the proportional control circuit is an estimate of the value required at the integral control circuit output (or the control input of the amplifier) for the amplifier output to achieve its desired output power when the vector modulator is at its full output level. The actual power output during estimation is relatively low since the vector modulator output is low, as discussed below.

30      During estimation mode, the vector modulator 120 is not at full output and may or may not be active. Depending on the modulation format, the vector modulator output may be zero or may be vacillating between zero and low

level outputs. This latter condition is common of a root raised cosine response vector modulator in the time before the modulator output ramps up to full power.

In one embodiment, estimation mode reference signal values for corresponding amplifier power outputs are preprogrammed and stored in memory, for example in a look-up table or in a Radio Logic Unit as illustrated in FIG. 2. In some applications, the estimation mode reference signal levels are also obtained for particular output power levels by sampling the output of the integral control circuit after a subsequent ramping mode of operation, discussed below.

In the exemplary embodiment of FIG. 1, the op-amp is configured as the unity gain buffer by closing switch SW1 so that the op-amp output will follow the reference signal applied to the positive input thereof. During estimation mode, in the exemplary embodiment of FIG. 1, switches SW2, SW3 and SW4 are also closed. In FIG. 1, a magnitude block 160 of a base band processor generates the estimation mode reference signal  $V_{ref}$  equal to  $V_{est}$ , which is input to the op-amp gain circuit. In the exemplary embodiment of FIG. 1, the switches SW1, SW2, SW3 and SW4 and the baseband processor are controlled by a processor 170.

In one embodiment, there is a filter between the reference signal source and the input of the proportional control circuit to control the bandwidth of the signal change at the reference input of the proportional gain control circuit and to reduce transient out of band power during estimation.

In the exemplary embodiment of FIG. 1, the filter is at the positive input of the op-amp 140 and comprises resistor  $R_{p1}$  and capacitance  $C_p$ . A typical RC time constant during Estimation Mode is  $R_{p1} * C_p = 0.2T_s$ , where  $T_s$  is the “Symbol Time”, which is the time between subsequent modulation symbols in a vector modulation system. This typical estimation mode RC time constant value is exemplary only and is not intended to limit the invention.

The estimation mode lasts generally for a sufficient time interval required for the proportional control circuit to reach steady state. In one embodiment, the estimation mode time period lasts for approximately 5 RC estimation mode time constants, although it may be more or less.

5 After estimation mode, the output of the vector modulator 120 is ramped upwardly to its full output power in ramping mode. Generally, during ramping, the initial control signal applied to the amplifier during estimation mode is corrected by integrating an output of the amplifier relative to a second reference signal. The second reference signal is generally proportional to the ramping output of the vector modulator and may be scaled for the desired output power.

10 In FIG. 1, ramping mode begins by opening switches SW1 and SW2 and configuring the magnitude block 160 to generate a reference signal  $V_{ref}$  proportional to the ramping output of the vector modulator. In this configuration, the op-amp 140 is configured as an integrator.

15 The RC time constant during ramping mode is generally greater than the RC time constant during Estimation Mode. Generally, Ramping Mode lasts longer than Estimation Mode. In one embodiment, the feedback capacitance  $C_m$  is equal to  $C_p$  and  $R_{m1}$  is equal to  $(R_{p1} + R_{p2})$ . The exemplary Ramping Mode RC time constant is approximately  $0.7T_s$ , which is slower than the exemplary RC time constant,  $0.2T_s$ , of the estimation mode. In one embodiment, the ramping mode lasts for approximately 3 to 3.5  $T_s$ .

20 In one embodiment, during ramping mode, the reference signal and the amplifier output are phase matched by delaying the reference signal applied to the integral control circuit with a delay means 162. The delay means 162 may be a delay circuit or software controlled delay of the signal.

During ramping mode, the reference signal,  $V_{ref}$ , increases in proportion to the ramping output of the vector modulator, scaled by whatever the desired output power should be as represented by the time average of the detected amplifier output signal. Ramping mode generally lasts long enough to allow transients to settle out by the end of the ramping mode.

If the reference signal,  $V_{est}$ , during estimation mode is exactly correct and if the peak-detect signal is a perfect representation of the amplifier output power, the reference signal and peak detect output track each other perfectly. Under these circumstances, the inputs at the integrator op-amp 140 are the same throughout the ramping mode ( $V_{ref}$  and the peak detect voltage are tracking perfectly and the time constants are the same) and the integrator output voltage remains the same as the estimation output applied to the amplifier control input. The control circuit will correct the amplifier output to the extent that the estimated output is incorrect without inducing transients.

During ramping mode, the transient out-of-band power spectrum is controlled by the bandwidth of the integral control circuit. In one embodiment, the bandwidth of the integral control circuit during ramping mode is reduced relative to the bandwidth of the proportional control circuit during estimation mode. If the ramping mode bandwidth is too low, however, the integral control circuit will not be sufficiently responsive. Thus there is a trade off between transient out of band power spectrum control and integral control circuit responsiveness.

After ramping mode, the control circuit operates in a "Modulation Mode". During modulation mode, the corrected control signal, which may or may not have been corrected during ramping mode depending on the accuracy of the estimation value, applied to the amplifier is maintained by applying a third

reference signal to the integral control circuit. The third reference signal is generally proportional to an averaged output of the amplifier.

In one embodiment, in modulation mode, the integral control circuit is configured to have a bandwidth that is less than the bandwidth thereof during  
5      ramping mode. In modulation mode, the integral control circuit corrects slow phenomenon such as supply line droop and thermal gain variations, but modulation variations are tracked poorly or at not all.

In the exemplary embodiment of FIG. 1, during modulation mode, the switches SW3 and SW4 are opened. The reference signal  $V_{ref}$  generated by the  
10      magnitude block 160 and applied to the input of op-amp 140 is based on or proportional to the average peak detector output for the desired amplifier power output. The magnitude block ignores inputs from  $V_{est}$  and from the output of the vector modulator 120. A typical integral gain circuit RC time constant for modulation mode is between approximately 40 and 400  $T_s$ . The switches SW3 and  
15      SW4 are controlled by the processor 170.

In some modes of operation, for example TDMA operating modes, modulation ends periodically. In one embodiment, the vector modulator is allowed to ramp down naturally when modulation ends. The relatively slow  
20      bandwidth of the integral control circuit in modulation mode will not react to the relatively rapid power reduction. The control circuit may be disabled upon ramping down the vector modulation without spectral considerations.

The amplifier control circuits of the present invention may also be implemented with digital circuit elements. The exemplary embodiment of FIG. 3 is a portion of a mobile TDMA communications device having a transmitter 300  
25      with a digital control system comprising generally an interface 310 that transmits digital vector modulation signals I/Q from a baseband processor to a digital I/Q



processing circuit 312 coupled to an amplifier circuit 314 by analog reconstruction filters 313.

5      A digital proportional control circuit comprising shift registers 320 provides stability. A digital integral control circuit comprises shift registers 330 and accumulator 332. In the digital implementation, during the estimation mode, the initial control signal is loaded directly into the register output of the accumulator. The output of the peak detect circuit 340 is processed with analog processing circuitry 350 and then digitized by an A/D converter 360.

10      The interface 310 provides digital reference signals via a register 316 from the baseband processor to the proportional control circuit and the integral control circuit. The register 316 delays at least some of the reference signals to the proportional and integral control circuits. The digitized output of the peak detection circuit 340 is summed with the digital reference signals provided by the baseband processor to provide an error signal to the integral control circuit.

15      The register 334 is not required for the TDMA format and provides a tolerable delay. The outputs of the proportional and integral control circuits are processed and converted by a processing and D/A circuit 370. The resulting analog control signal is processed by an analog processing circuit 380 before coupling to the control input of the amplifier circuit 314.

20      FIG. 4 illustrates a timing diagram for an exemplary IS-136 TDMA application with the operating modes discussed above. TDMA estimation mode operation begins with the rising edge of a DMCS signal. After a delay interval set by PAC\_DLY, the detected RF output voltage is reduced by a residual offset. At this point there is no amplifier output. A RAMP\_DLY signal is set to align the  
25      Ramp waveform with the modulated RF waveform.

Next, a delay INIT\_DLY sets the point at which the accumulator, and thus the AOC D/A of FIG. 3, are set at the estimated value of ACC\_INIT. In FIG. 3, the control output to the amplifier is smoothed by the digital filter on the AOC D/A input 370 and the analog filter 380 on the AOC D/A output and thus does not contain discontinuities shown for the accumulator output. The amplifier output will be proportional to the detected voltage.

After a time interval EST\_DLY, the TDMA ramping mode begins and the input to the accumulator is switched to the error between the detected signal and the ramping waveform. During this time, the integral control circuit loop is closed and configured with a first bandwidth setting of ERRGain1. In FIG. 3, the digital filter on the D/A input is bypassed at this time, since it is no longer required for bandwidth control and may compromise loop stability.

In FIG. 3, the value of the output register 334 is stored when CDET\_DLY expires at or just before the end of the ramping mode for subsequent TDMA bursts.

TDMA modulation mode begins upon expiration of time interval BW\_DLY. The integral control circuit is configured with a bandwidth setting of ERRGain2.

Finally, after the amplifier output falls with I/Q modulation shaping to zero, the DMCS signal goes low to signify the end of the I/Q data. After a delay DN\_DLY, the AOC section 370 in FIG. 3 is powered down. This example assumes zero delay, thus DN\_DLY is shown as zero. In practice, DMCS will fall prior to DN\_DLY expiring.

The exemplary embodiment of FIG. 5 is a portion of a mobile EDGE communications device having a transmitter 500 with a digital control system comprising generally a phase map output 510 that transmits digital vector

modulation signals from a baseband processor to a digital I/Q processing circuit 512 to the amplifier circuit 514 via analog reconstruction filters 513.

A digital proportional control circuit comprising shift registers 520 provides stability. A digital integral control circuit comprises shift registers 530 and accumulator 532. In the digital implementation, during the estimation mode, the initial control signal is loaded directly into the register output of the accumulator. The output of the peak detect circuit 540 is processed with analog processing circuitry 550 and then digitized with an A/D converter 560.

In FIG. 5, reference signals are provided to the proportional control circuit and the integral control circuit under control of a baseband processor. The ramping values are stored in a table 516 and are scaled by a factor, PWR, for the desired power output. This is possible because in the EDGE format, the ramping values are not data dependent. Each transmission may thus use the same ramp-up pattern. This eliminates the need to send the ramping values across the digital interface, as was required in the TDMA system of FIG. 3. The digitized output of the peak detection circuit 540 is summed with the digital reference signals provided by the baseband processor to provide an error signal to the integral control circuit.

The digital outputs of the proportional and integral control circuits are converted to analog form by a D/A circuit 570. The resulting analog control signal is also processed by an analog processing circuit 580 before coupling to the control input of the amplifier circuit 514.

FIG. 6 illustrates a timing diagram for an exemplary EDGE application with the operating modes discussed above. EDGE estimation mode operation begins with the rising edge of a DMCS signal. After a delay interval set by PAC\_DLY, the detected RF output voltage is reduced by a residual offset. At

this point there is no amplifier output. A RAMP\_DLY signal is set to align the Ramp waveform with the modulated RF waveform.

Next, a delay INIT\_DLY sets the point at which the accumulator and thus the AOC D/A of FIG. 5 are set at the estimated value of ACC\_INIT. In FIG. 5,  
5 the control output to the amplifier is smoothed by the analog filter 580 on the AOC D/A output and thus does not contain discontinuities shown for the accumulator output. The amplifier output will be proportional to the detected voltage.

After a time interval EST\_DLY, the EDGE ramping mode begins and the input to the accumulator is switched to the error signal between the detected  
10 signal and the ramping waveform. After a delay RAMP\_DLY to permit suppression of leading low-resolution signals, the Ramp signal begins. During this time, the integral control circuit loop configured with a first bandwidth setting of ERRGain1.

EDGE modulation mode begins upon expiration of time intervals  
15 BW\_DLY and DIV\_DLY. The integral control circuit is configured with a bandwidth setting of ERRGain2, which is generally much lower than the TDMA modulation mode bandwidth. In FIG. 5, the value of the output register 534 is stored when CDET\_DLY expires for subsequent bursts.

In another alternative embodiment, an output register 534 is held at  
20 the expiration of DIV\_DLY. This prevents the AOC control circuit from having a detrimental effect on EDGE modulation fidelity. This is equivalent to setting a low bandwidth with ERRGain2. Finally, after the amplifier output falls with I/Q modulation shaping to zero, the DMCS signal goes low to signify the end of the I/Q data. After a delay set by DN\_DLY, the AOC section 570 in FIG. 5 is powered  
25 down. This example assumes zero delay.

The exemplary embodiment of FIG. 7 is a portion of a mobile GSM communications device having a transmitter 700 with a digital control system comprising generally a differential encoder 710 coupled to a digital I/Q processing circuit 712 coupled to an amplifier circuit 714 via analog I/Q reconstruction filters 713.

In FIG. 7, a digital proportional control circuit comprising shift registers 720 provides stability. A digital integral control circuit comprises shift registers 730 and an accumulator 732. In the digital implementation, during the estimation mode, the initial control signal is loaded directly into the register output of the accumulator. The peak detect circuit 740 output is processed with analog processing circuitry 750 and then digitized with an A/D converter 760.

In FIG. 7, reference signals are provided to the proportional control circuit 720 and the integral control circuit 730 under control of a baseband processor. The ramping values are stored in a table 716 and are scaled by a factor, PWR, for the desired power output. This is possible because in the GSM format, a common ramping pattern is imposed on the modulation for each transmission. This eliminates the need to send the ramping values across the digital interface, as was required in the TDMA implementation of FIG. 3.

The processed and digitized output of the peak detection circuit 740 is summed with the digital reference signals provided by the baseband processor to provide an error signal to the integral control circuit. The register 734 is not required for the GSM format and provides a tolerable delay. The outputs of the proportional and integral control circuits are processed and converted by a processor and D/A circuit 770. The analog control signal is also processed by an analog processing circuit 780 before coupling to the control input of the amplifier circuit 714.

The data, which includes phase information in GSM format, loaded by the circuit 710 and the I/Q Ramp Up signal, which includes amplitude information, are synchronized with each other and with the AOC Ramp Up Start signal so that the summed signals forming the error signal applied to the integral control circuit are phased matched.

FIG. 8 illustrates a timing diagram for an exemplary GSM application with the operating modes discussed above. GSM estimation mode operation begins with the rising edge of a DMCS signal. After a delay interval set by PAC\_DLY, the detected RF output voltage is reduced by a residual offset. At this point there is no amplifier output. Next, a delay INIT\_DLY sets the point at which the accumulator and thus the AOC D/A of FIG. 8 are set at the estimated value of ACC\_INIT.

In FIG. 7, the control output to the amplifier is smoothed by the analog filter 780 on the AOC D/A output and thus does not contain discontinuities shown for the accumulator output. The amplifier output will be proportional to the detected voltage.

After a time interval EST\_DLY, the GSM ramping mode begins and the input to the accumulator is switched to the error between the detected signal and the ramping waveform. After a delay RAMP\_DLY, the Ramp signal begins. G\_IQ\_DLY expires at approximately the same time so that RF input rises with the ramping waveform, since both look-up tables are defined by the same function. During this time, the integral control circuit loop is closed and configured with a first bandwidth setting of ERRGain1.

GSM modulation mode begins upon expiration of time interval BW\_DLY. The integral control circuit is configured with a bandwidth setting of ERRGain2. The value of the output register is stored when CDET\_DLY expires.

Upon expiration of a delay DIV\_DLY, the integral control circuit enters a hold mode just before modulation ends. Finally, after the amplifier output falls with the ramp pattern imposed by the I/Q multipliers. The DMCS signal goes low to signify the end of the I/Q data. After a delay set by DN\_DLY, the AOC section 770 in FIG. 7 is powered down. RAMP\_DN\_DLY is shown as zero in the diagram since zero delay is assumed. In practice, it will occur somewhere after the falling edge of the DMCS because of system delays.

While the present inventions and what is considered presently to be the best modes thereof have been described in a manner that establishes possession thereof by the inventors and that enables those of ordinary skill in the art to make and use the inventions, it will be understood and appreciated that there are many equivalents to the exemplary embodiments disclosed herein and that myriad modifications and variations may be made thereto without departing from the scope and spirit of the inventions, which are to be limited not by the exemplary embodiments but by the appended claims.

What is claimed is: